Operational Altimeter-Derived Oceanographic Information: The NORDA GEOSAT Ocean Applications Program

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ABSTRACT

The U.S. Navy’s GEOSAT active microwave altimeter provides detailed oceanographic and atmospheric information. It measures global oceanic wind speeds and significant wave height, sea ice edge in the polar regions, and dynamic topography related to mesoscale ocean circulation. The Naval Ocean Research and Development Activity processed near-real-time GEOSAT data to monitor oceanic processes from July 1985 to January 1989. We found that the combination of topographic information from GEOSAT, synoptic sea surface temperature information from infrared imagery, and local information from bathythermographs provides valuable information on Gulf Stream circulation. The size of the area involved, the intensity of currents, and the rapidity with which changes occur previously limited our technical ability to observe the Gulf Stream and its attendant spin-off eddies. Long-term study with the information sources described above has given a more complete picture of the Gulf Stream region’s mesoscale circulation than ever before achieved.

1. Introduction

The Naval Ocean Research and Development Activity (NORDA; since 10 October 1989, NORDA has been the Naval Oceanographic and Atmospheric Research Laboratory) routinely prepared an analysis of mesoscale ocean features in the northwest Atlantic Ocean’s Gulf Stream region from U.S. Navy GEOSAT (GEOccy Satellllte) altimeter measurements, infrared (IR) imagery, and in situ temperature data. The GEOSAT Ocean Applications Program (GOAP) provided the mesoscale analysis and three other types of altimeter-derived oceanographic information on a regular schedule for over 3 years, July 1985–January 1989, following several years of preparation. GOAP’s purpose was to conduct an operational demonstration of the altimeter’s usefulness to collect timely, accurate global environmental data, to process the data in near real time, and to transmit the products to the Navy’s Fleet Numerical Oceanography Center (FONOC) for use in routine analysis and prediction of oceanographic parameters (Clancy 1987). As an operational demonstration GOAP was effectively a feasibility study, in which NORDA derived oceanographic information from GEOSAT altimetry and transmitted the results to a Navy operational environmental center on a quasi-operational schedule.

Altimetry is not as severely hampered by cloud cover as IR imagery, and it also measures oceanographic phenomena which have no surface thermal expression. The topographic information that the altimeter provides can be used to detect oceanographic features whose surface thermal signatures are masked by atmospheric effects (e.g., water vapor) or covered by clouds. Another source of difficulty with IR imagery is that the warming of the ocean’s surface layer during spring and summer tends to obscure cold-core rings south of the Gulf Stream. Altimeter measurements frequently increase the amount of detail in mesoscale analyses when they are used to supplement IR imagery as an information source. NORDA produced two mesoscale analyses per week during GOAP. The GOAP mesoscale analyses were incorporated into the FONOC system (Clancy 1987) and provided to a Navy regional oceanographic center.

GOAP also provided daily global information on surface wind speed and significant wave height, and sea ice edge in both the Arctic and Antarctic regions. All three of these “product” types have substantially increased the amount of information available to the Navy on these oceanographic parameters. GEOSAT only has one ground station, which restricts the number of times per day data can be received. This, in turn, severely limits the quantity of wind and wave data timely enough to be used in FONOC analyses. However, retrospective studies have shown that the information has the potential to be of value (e.g., Pickett et al. 1987). The sea ice edge information produced has been used routinely (Hawkins and Lybanon 1989). This paper describes the production of all four types of oceanographic information from GEOSAT altimetry, but will

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concentrate primarily on mesoscale feature analysis. The latter sections of the paper discuss interpretive techniques, give examples of the information that altimetry contributes to the analysis, and present some conclusions drawn from the 3-year GOAP analysis results. In particular, section 5b gives Gulf Stream position information derived from the GOAP mesoscale analyses.

2. Background

GEOSAT was built by the Johns Hopkins Applied Physics Laboratory (APL) and launched on 12 March 1985, into an 800-km altitude, 108-degree inclination orbit. The initial orbit generated a ground track pattern that almost repeated every 3 days, and had an average ground track spacing of 4 km at the equator by the end of the 18-month-long primary mission (McConathy and Kilgus 1987). The satellite carries a single instrument, a 13.5 GHz nadir-looking radar altimeter similar to the SEASAT altimeter in its mechanical, thermal, and electrical interfaces, but with some engineering changes intended to extend its lifetime and reduce its noise level (MacArthur et al. 1987).

GEOSAT's primary mission was to provide the dense global grid of altimeter data required to improve knowledge of the earth's gravitational field. Collection of altimeter data for oceanographic and meteorological investigations was the secondary mission during the first 18 months of GEOSAT, but it became the primary mission thereafter. The Oceanographer of the Navy formulated GOAP, an oceanographic analysis program, to improve the overall value of the GEOSAT data. After over 3 years of successful operation, NORDA transitioned GOAP to operational status at the Naval Oceanographic Office (NAVOCEANO).

On 1 October 1986, APL began maneuvers that placed the spacecraft into a 17-day exact repeat orbit optimized for collecting oceanographic data. The subsequent GEOSAT Exact Repeat Mission (ERM) was designed so that long-term, along-track averaging could give an accurate local mean sea surface, and minimize the errors that occur when an imperfectly known marine geoid is subtracted from the altimeter data to produce mesoscale dynamic topography. The ascending nodes of the exact repeat orbit are approximately at 1.004 + n(1.4754)°E longitude, where n is an integer between 0 and 243. Thus, the ground track is a network that repeats every 244 revolutions, with a spacing of about 120 km in the Gulf Stream region. The orbit is adjusted as necessary to maintain this pattern laterally within less than 1 km. The ERM began on 8 November 1986.

3. GOAP processing

a. Data system

The altimeter transmits 1020 pulses per second and measures the return waveforms. Averaging aboard the spacecraft reduces the data rate by a factor of 100, so measurements are transmitted to the ground at a rate of approximately 10 per second. The APL ground station receives the data approximately every 12 hours and produces NORDA Data Records (NDRs), which contain measured range, significant wave height, wind speed, and automatic gain control (all except wind speed at a 10-per-second rate), plus mode and data quality flags, and corrections for satellite and instrument errors. APL promptly transmits the NDRs to NORDA over a 9600-baud dedicated telecommunication circuit. During GOAP NORDA derived oceanographic products from the NDR data and transmitted them to FNOC over a similar circuit, using the standard Data Exchange Formats endorsed by the Federal Coordinator for Meteorological Services and Supporting Research (U.S. Dept. of Commerce, NOAA, 1982).

Both telecommunication links used 9600-baud, dedicated telephone lines but different communication protocols. The NORDA-APL line used an IBM binary synchronous protocol with line control software written by APL. The hardware interface was based on the Gould Systems Engineering Laboratories Model 9116 Binary Synchronous Line Interface Module. The NORDA-FNOC line used the X.25 protocol. NORDA's computer was interfaced to that line via a Com-Design TX-700 X.25 Packet Assembler/Disassembler.

NORDA's GOAP information processing system hardware consisted of two Gould Systems Engineering Laboratories 32/27 32-bit minicomputers with associated peripherals, including International Imaging Systems (I2S) image processing hardware. The software had four types of elements: communications and file management, real-time processing, objective processing, and interactive processing.

The first element performed line-control functions for the two data links and transferred files between disks and the telecommunication lines. The second produced the scalar wind, significant wave height, and ice edge products. The third involved such functions as earth location, land/sea determination, bad point editing and averaging, geophysical corrections, height residuals calculation, etc. The fourth covered operations used in the subjective generation of the mesoscale product (discussed in a later section). That element was primarily comprised of I2S System 575 software, a proprietary interactive command interpreter with an associated image processing library designed to operate with I2S Model 75 hardware.

Quality control was an important part of the processing to derive the oceanographic products. Some quality-control tests checked "flags," i.e., one-bit indicators. The NDR contains two types: mode flags and data quality flags. A mode word, made up of three status/mode words from the spacecraft's telemetry stream, contains the mode flags, which indicate the altimeter's operational status, details about its acquisition of the return signal, etc. The data quality flagword contains the results of tests performed during ground
processing at APL, which determine the statistics and “reasonableness” of measured and calculated quantities (Cole 1985).

The quality control checks that were performed for all products are status flag, mode word, missing data, and time checks.

Status flag check. Each GEOSAT record (approximately 5 s of data) in the NDR has an associated status flag, which tells whether the data have been received by APL and whether the data have been sent to NORDA. (The NDR is a direct-access file, which is not necessarily filled in time order.)

Mode word check. Each GEOSAT subrecord (approximately 1 second of data) contains the mode word described above. Data were considered good when the flags indicated that GEOSAT was in the proper operational mode and valid data was received.

Missing data check. The data quality flagword in each subrecord consists of 27 flags. The flags were checked for the presence or absence of height, significant wave height, and automatic gain control (AGC) values.

Time check. Each NDR contains data for 1 day, nominally to within less than a second. The NDR provides two sets of time tag data, which are used to compute time for each GEOSAT subrecord. The time per frame was obtained by differentiating the two time tags. This time must be within 0.001 s of 0.098 s per frame. If the 0.001 s variance condition was met, the time for the start of the NDR was computed using the start frame count. The start time had to be within 60 s of the start of day (UTC) for the NDR to be processed.

b. Oceanographic parameters

1) Scalar wind speed and significant wave height

The change in the microwave signal’s surface reflectivity due to the wind-driven surface roughness provides an altimeter estimate of surface scalar wind speed. The algorithm employed at APL (Brown et al. 1981) is

\[ W = \exp[(S - B)/A], \]  

where

\[ S = 10^{-1[10^{\sigma^o} + 2.1]/10}. \]  

In these equations, 

- $W$ wind speed at 10 meters above the ocean surface,
- $\sigma^o$ radar backscatter cross section,
- $A, B$ constants for 3 different $\sigma^o$ ranges.

The $\sigma^o$ is inferred from the altimeter’s AGC signal. The complete Brown algorithm is a two-stage procedure. Equations (1) and (2) define the first stage. The second stage calculates an improved wind speed estimate, a fifth-degree polynomial function of the $W$ given by Eq. (1). The latter calculation compensates for skewness in the distribution of the difference values between buoy- and altimeter-measured wind speed (Brown et al. 1981). The estimate of backscatter is highly sensitive to an off-nadir pointing error; consequently, such an error would corrupt the wind speed estimate. A separate calculation corrects backscatter for the off-nadir pointing error (Cole 1985), prior to its use in Eq. (2). That calculation makes use of a parameter called VATT, which is described in the index discussion. The off-nadir correction to backscatter effectively corrects wind speed for pointing errors.

The reflecting surface modulates the transmitted pulse. More specifically, ocean waves stretch the return waveform’s leading edge, so that its slope provides an estimate of significant wave height (SWH); higher waves produce smaller slopes. The SWH calculation is performed aboard the GEOSAT spacecraft and the results are transmitted to the ground station.

APL calculates both wind speed and wave height. During GOAP NORDA edited the values for data quality, averaged the wave height values to a once-per-second rate (APL supplies wind speed at that rate), put the resulting edited, once-per-second wind and wave values into a wind-wave record, and transmitted them to FNOC. FNOC uses the GEOSAT wind speed data in their marine wind analysis, while the significant wave height data are an input to the FNOC visual sea height analysis.

Dobson et al. (1987) compare GEOSAT wind speed and significant wave height measurements to in situ observations. Their overall conclusion is that the wind speed measurements agree within 1.8 m s$^{-1}$ and wave height measurements agree within 0.49 m. Monaldo (1988) discusses two related topics: What are the expected differences between buoy and altimeter estimates of these quantities, and what conclusions can be drawn about the capacity of an altimeter to measure them.

NORDA applied several special data quality checks to the wind speed and wave height values. The data quality flagword was checked for height, AGC, and SWH standard deviations out of bounds. Also, there was a check of the “VATT not available” flag. These flags indicate problems with the wind or wave data in the subrecord. A least-squares fit of a straight line was performed on the SWH data that passed the prior data quality checks. Then, any SWH value more than two standard deviations from the fitted line was marked bad in the processing software’s internal data quality flags.

2) Sea ice edge

The return pulses from sea ice have a significantly different shape than returns from the ocean (Eppler
1982). Dwyer and Godin (1980) developed a semiempirical algorithm for the GEOS-3 altimeter that measures those differences. That algorithm, as modified for GEOSAT, is

\[
\text{index} = \frac{[(100 + \text{AGC})/(100 \times \text{VATT})]}, \quad (3)
\]

where

AGC  automatic gain control signal,
VATT “voltage” proportional to attitude (dimensionless)

\[
\text{VATT} = \frac{[\text{ATTG} - \text{ATTGE}]/(\text{AGCG} - \text{ATTGE})]}{(4)
\]

and the intermediate quantities are functions of the 60 basic return pulse waveform samples [the sample indexing is the same as for the SEASAT altimeter (MacArthur 1978)]

ATTG  mean of last 8 samples,
ATTGE mean of first 8 samples,
AGCG  mean of center 48 samples (not including the track point gate).

This “ice index” is a number in the range of 0.6–0.7 over water and is greater than 1 over ice. (That threshold is based on a prelaunch simulation that used SEASAT data.) So, water–ice transitions are evident in the ice index’s time history.

As in the case of the other oceanographic products, the ice products are based on 1-second average values of altimeter-derived quantities. NORDA provided alphanumeric ice index data files for both the Northern and Southern hemispheres. In addition, NORDA prepared daily ice index plots and transmitted them to the Naval Polar Oceanography Center (NPOC) via FNOC (Hawkins and Lybanon 1989). The graphic products are the same size and projection as NPOC’s other working charts, which facilitates their use. Figure 1 shows a sample ice index graphic product.

The graphic products show ice index profiles over water, with the satellite’s nadir tracks as base lines (Hawkins and Lybanon 1989). Their interpretation to delineate water–ice transitions is suggested above. The point along a ground track where the ice index rises above the threshold clearly indicates the ice edge. The threshold value was modified from 1.0 to 0.9 after NORDA and NPOC gained experience in interpreting GEOSAT ice index data. NORDA is continuing research efforts designed to extract more information from the ice index.

NORDA performed two data quality checks during the ice index processing. A least-squares fit was used to eliminate AGC outliers, as was done for SWH data. Also, VATT values less than 0.0 or greater than 2.2 were excluded.

3) Sea Surface Height Measurement

The radar altimeter measures the distance from its antenna’s electrical center to the instantaneous sea surface as averaged over the footprint. The effective (pulse-limited) footprint is a function of significant wave height. The footprint’s radius is

\[
r = \sqrt{hc}\tau'
\]

where \( h \) is the satellite’s altitude, \( c \) is the speed of light, and the effective pulse duration \( \tau' \) is

\[
\tau' = \left[ \tau^2 + \left( \frac{H}{c} \right)^{2/3} \right]^{1/2}.
\]

In Eq. (6) \( \tau \) is the pulse duration (3.125 ns for GEO-SAT) and \( H \) is wave height. GEOSAT’s footprint diameter is 1.7 km for a perfectly flat sea, increases to 2.1 m for 1-m waves, 4.0 m for 5-m waves, and 5.6 m for 10-m waves. [Brooks et al. (1978) provide a helpful diagram and the correct equation for flat seas. For rough seas the pulse duration is replaced by the effective pulse duration of Eq. (6).]

Sea level is the difference between the altimeter-measured distance and the satellite’s height, where the latter is determined independently by tracking and orbit determination. (Orbit height is normally referenced to a standard “reference ellipsoid”; consequently, so is sea level.) Then, the difference between sea level and the geoid, the sea surface height (SSH) residual, provides information on ocean dynamics.

The GEOSAT altimeter provides dense, all-weather range measurements along the satellite’s nadir track with 3.5-cm precision (MacArthur et al. 1987) and an average white-noise level of about 8 cm (Sailor and LeSchack 1987). Conversion to SSH residuals requires orbital calculations (both for earth location and satellite height determination), correction for orbit error and other geophysical error sources, and removal of the geoid or other reference surface. Lybanon and Crout (1987) discuss the error sources and provide estimates of their magnitudes.

NORDA performed one data quality check specifically for SSH processing: A least-squares fit was used to eliminate altitude height word outliers, as was done for SWH and AGC (the latter during ice processing) data.

Available “geoids” are not true geoids; they contain errors. These geoids generally include information derived from altimeter data, taking advantage of the fact that the long-term mean of altimeter-derived sea level is approximately the marine geoid. (The EUR’s repeat orbit provides the opportunity to use along-track ensemble means as reference surfaces for the SSH computation. In some areas these are the best “geoids” available.) However, that mean also includes the time-independent part of the dynamic topography. The presence of this contaminating term significantly interferes with interpretation of the SSH residuals.

It is impossible to separate this part without independent information. The construction of so-called “synthetic geoids” by removal of the mean oceanography contamination is a topic of considerable current interest. Kilgus (1989) reports on several synthetic
geoid methods (detailed descriptions have been submitted for publication by the researchers), all of which introduce additional information to achieve the separation. Tapley et al. (1988) describe a different approach which uses altimeter data, tracking data, and surface gravity data to solve simultaneously for the sea surface topography, the Earth’s gravity field, the satellite’s orbit, and other parameters.

Figure 2 illustrates the problem. The dashed line in Fig. 2a shows an idealized mean Gulf Stream height profile, which is often present as a geoid error. The three solid lines are instantaneous Gulf Stream SSH profiles as they would appear if they could be calculated without error. The mean is “smeared” because of the Gulf Stream’s meandering while the altimeter data incorporated in the geoid were collected, and possibly because of filtering used in the geoid’s construction.

The mean Gulf Stream’s amplitude is shown as less than that of the instantaneous Gulf Stream profiles, another possible effect of the filtering. The three instantaneous profiles include one north of, one coincident with, and one south of the mean Gulf Stream’s position. Figures 2b, 2c, and 2d show the result of differencing the instantaneous and mean profiles, as in the subtraction of the “contaminated” reference surface from sea level. In general, both the resulting profile’s shape and, to a smaller extent, its position are affected. (Although it is not apparent from the plots, the amplitude of the variation in Fig. 2c is smaller than that for the other two.) Several NORDA efforts are in progress to account for and correct the geoid error caused by the presence of mean oceanography. Kilgus (1989) describes preliminary results from some of them.

An added benefit can result from performing this
Fig. 2. Effect of mean oceanography in reference surface upon SSH residuals. Subtraction of reference surface induces error in residuals. (Top) Mean Gulf Stream profile and 3 instantaneous ideal (error-free) Gulf Stream SSH profiles. (Case 1) Difference, instantaneous Gulf Stream north of mean Gulf Stream. (Case 2) Difference, instantaneous Gulf Stream coincident with mean Gulf Stream. (Case 3) Difference, instantaneous Gulf Stream south of mean Gulf Stream.

calculated by the Navy Astronautics Group, became available.

Simple linear detrending was adequate to reduce the residual orbit error to the centimeter level for the relatively short tracks (2000 km or less) through the GOAP mesoscale test area. To a good approximation, the orbit error is sinusoidal with a period equal to the orbital period. It is not quite adequate to expand the sinusoid in a Taylor series and look at the magnitude of the first term beyond the linear term to estimate the residual error, because there is also a phase angle, i.e., the 2000-km segment may be any (small) "piece" of the sinusoid. However, a simple computer simulation shows that for 10–20 m orbit errors, the mean rms error after removing a straight line is under 5 cm. A slightly different analysis shows that the maximum value of the residual nonlinear error is 1.2 cm per meter of orbit error.

This "tilt and bias correction" simultaneously took care of the other long-wavelength errors that affect the mesoscale analysis. Ocean tides, electromagnetic (EM) bias, and the wet tropospheric pathlength correction were addressed explicitly, because they have significant energy at mesoscale wavelengths.

Tides were calculated from the Schwiderski model (Schwiderski and Szteto 1981), which has an accuracy of 10 cm or better over open ocean. EM bias, an apparent shift in sea-surface elevation caused by a difference in strength of the reflection from the troughs and crests of ocean waves, can be modeled adequately as a range error proportional to significant wave height. The altimeter's electronic tracker is responsible for a similar bias; GOAP used a combined correction factor of 5 percent of significant wave height (Born et al. 1982). MacArthur (APL, private communication, 1989) thinks that 5 percent is a reasonable value.

The tropospheric water vapor pathlength error may have a magnitude of 25 to 30 cm, and a local (i.e., in the mesoscale range) variability of 10 to 20 cm (Hawkins and Smith 1986). NORDA's processing software provided for this correction, although no good means of determining it was available during the GOAP operational demonstration. Because the mesoscale topographic signals of interest in the Gulf Stream region are of the order of 50–100 cm, a major impact on the location of mesoscale features was not expected, and not observed very often. NORDA is now using a correction based on observations from the recently launched Special Scanner Microwave/Imager (SSM/I) radiometer. Algorithms to calculate an SSM/I wet troposphere correction were developed by J. Hollinger (1980). Tapley et al. (1982) showed that the water vapor correction based on SEASAT Scanning Multichannel Microwave Radiometer (similar to SSM/I) measurements was realistic. Phoebus and Hawkins (1990) discuss the significance of the water vapor correction (calculated from SSM/I measurements) in the northeast Pacific Ocean, where the oceanographic signals are much smaller.
4. Mesoscale analysis

a. Background

NORDA prepared a description of Gulf Stream region mesoscale ocean features beginning in the fall of 1985, first at 10-day intervals and later twice each week. This was a logical continuation of work begun in the 1970s by NAVOCEANO scientists, who studied the Gulf Stream and rings and published results in the Gulf Stream Monthly Summary and later in Gulf Stream (1975–1981). The latter publication has since been replaced by the Oceanographic Monthly Summary. Maps based on satellite image analyses, which show the positions of the Gulf Stream and rings, have also been produced weekly by the Naval Eastern Oceanography Center (NEOC) and several times a week by the National Oceanic and Atmospheric Administration (NOAA). GOAP’s important contribution was the introduction of the altimetric signal into the interpretive process. Altimetry’s advantages are all-weather capability and close connection of the measurement with ocean dynamics, as discussed in Section 3b(3). The GOAP analyses covered the area outlined in Fig. 3, and provided information of operational use to the Navy. Recently, eddy-resolving regional models for the Gulf Stream were developed (Robinson et al. 1988), and comparisons between the two outputs and analyses of the differences are being studied. GEOSAT data are being used to test and refine them.

Cheney and Marsh (1981) verified the presence of dynamic ocean features in SEASAT altimeter profiles. Cheney (1982) combined 2 weeks of satellite IR imagery, bathythermograph (BT) data, and drifter trajectories into Gulf Stream region mesoscale feature maps. These maps were compared to SEASAT altimeter profiles to determine the altimeter data’s usefulness in finding the mesoscale features. Based on the successful results of these comparisons, NORDA took the analysis one step further. Latitude and longitude positions of the north and south walls of the Gulf Stream and of ring centers and edges, from altimeter SSH residuals, were combined with 3 to 4 days of IR imagery and 1 week of expendable bathythermograph (XBT) data to produce a mesoscale map of the Gulf Stream twice weekly. This map, referred to as the GEOSAT mesoscale map, was produced starting in September 1985.

SEASAT altimeter data showed that the Gulf Stream and its associated rings display a topographic signal of approximately 0.5 to 1.0 m (Cheney and Marsh 1981). Nevertheless, it is difficult to interpret altimetric signals in the Gulf Stream area. This portion of the paper discusses some of these difficulties, describes the steps in the preparation of mesoscale maps, and shows some preliminary statistical results derived from them.

b. Features

The Gulf Stream alone is a complicated oceanographic feature whose investigation goes far back into the last century. Stommel’s book, Gulf Stream (1965), one of the classics of oceanographic literature, summarizes earlier works and started an era of new investigations. Satellite IR imagery immensely enhances the understanding of the Gulf Stream’s complexity. Altimetry provides the means for identifying its location, and shows promise for giving more detailed and quantitative information concerning the mesoscale flow field. Figure 4 shows the altimetric signal across the Gulf Stream. The figure plots the SSH residual, the difference between sea level and the geoid, after corrections, as described in Section 3b(3).

Gulf Stream rings are a vital component of the Gulf Stream system. A ring is a special type of eddy that forms from a cut off Gulf Stream meander (Stommel 1965; Fuglister 1972; Richardson 1983). Rings are among the most energetic eddies in the ocean, and
their thermocline displacements, swirl speeds, and volume transports are nearly equivalent to the Gulf Stream's. They change their shapes and positions, sometimes rapidly, and interact with the Gulf Stream and other rings. They generate mean flow and are vital in transporting different water masses across the Stream (Newton 1961; Cheney and Richardson 1976).

c. Cold-core rings

Fuglister (1972) and Doblar and Cheney (1977) describe the creation of cold-core rings (CCRs). A CCR consists of a closed segment of the Gulf Stream that swirls cyclonically around a cold slope water core. Due to their initial surface temperature distribution, newly formed rings can be observed in satellite IR imagery. Richardson summarized their properties (1983). A new CCR is elliptical but becomes nearly circular as it moves away from the Gulf Stream. Typical diameters are 150 to 300 km. SEASAT altimeter observations showed that CCR sea surface depressions are approximately 0.5 to 1.0 m (Cheney and Marsh 1981). Figures 5, 6, and 7 show examples of the GEOSAT altimetric cold ring signals. Satellite ground tracks serve as baselines for the SSH plots.

Figure 5 shows the altimetric signal's all-weather advantage over IR images; both ascending tracks (year days 119 and 122) show the presence of a large (200-km diameter) CCR invisible in the IR, hidden under cloud cover. The ring is marked as "A" in the figure. Ring A appears in the IR satellite image from 4 days later (Fig. 6), and is intersected by year day 123's descending track. The "young" CCR shows a very symmetric 80-cm depression with the swirl velocity increasing with distance from the center. The SSH gradient indicates a surface velocity maximum of 200 cm s⁻¹ 60 km from the center, with a doppler farther from the center. This agrees with in situ observations (Olson 1980).

In the ring's central part, the near-surface rotation period is about 2 days. It is important to notice the ring's extent. Gulf Stream and Sargasso Sea waters are entrained into the ring, while the cold slope water, visible as a light-colored center, has a diameter of only 80 km. An "older" CCR, ring B, is visible in Fig. 6 in the lower center of the IR image, and it is partly visible in Fig. 7. Infrared imagery indicates that this ring did not move during this 10-day period. It was crossed by an ascending altimeter track on year day 133. That SSH profile shows a 40-cm depression and a 150-km diameter, with maximum surface current speed of 100 cm s⁻¹.

Cold-core ring interactions with the Gulf Stream fall into two categories (Richardson 1983). In the first the ring reattaches to the Gulf Stream. The ring center opens to the north of the Gulf Stream, and an open meander is created. Later, this ring is completely absorbed by the Gulf Stream. In the second category a "nonfatal" interaction occurs when a ring becomes attached to the Gulf Stream, moves downstream, and detaches from the Gulf Stream to form a modified ring.

Figure 8 shows an interaction of the first type. Part of the Gulf Stream is still visible in the altimeter signal north of ring C. The altimeter track on year day 73 crosses the ring, and a large, slightly asymmetric dip in the altimeter data (150 cm) is clearly visible. Figure 9 shows the altimeter data in detail (upper plot) with the corresponding geostrophic velocity profile (lower plot). Geostrophic velocity was computed from SSH data using a finite-difference approximation to the derivative. The SSH data were first filtered by a median filter (Gallagher and Wise 1981). Figure 9 also shows the importance of accounting for centrifugal force in the geostrophic velocity computation. The solid-line curve in the lower plot was obtained by a straightforward geostrophic calculation, while the dashed-line curve shows the velocity obtained by including centrifugal force.

d. Warm-core rings

Warm-core anticyclonic rings form (by pinching off) from the Gulf Stream throughout the slope water in a region bounded by the Gulf Stream and the continental slope. Their diameters are around 100 km. A warm-core ring (WCR) consists of an annular area of Gulf Stream water surrounding a Sargasso Sea core (Gotthardt 1973; Bisagni 1976; Lai and Richardson 1977; Halliwell and Moores 1979).

WCRs move westward with a mean speed of 5 cm s⁻¹, which is the mean slope water flow speed, and as they drift westward they gradually shrink in size. They interact very often with the Gulf Stream, sometimes separating, sometimes coalescing with it. They entrain the slope water and sometimes the shelf water, and advect it around and into the Gulf Stream (Morgan and Bishop 1977). When WCRs reach Cape Hatteras, they coalesce with the Gulf Stream (Gotthardt and Potocky 1974). An interdisciplinary study of WCRs was carried out in 1981 through 1985; results are published in JGR: Warm-Core Rings Collection (1985).

Figure 5 shows a WCR (ring D) interacting with the Gulf Stream. A large amount of Gulf Stream water is entrained into the ring. An ascending altimeter track that crossed this WCR 3 days before this IR image was taken shows the warm ring extending about 150 km with a 50-cm altimeter signal. The second WCR visible in this IR image is ring E, which is clustered near 40°N, 65°W. Figure 6 shows ring D as a very compact warm ring which redeveloped 4 days after interaction with the Gulf Stream. No altimeter track crossed this WCR until year day 131, 5 days later. That track, which intersects one edge of ring D, shows a large signal, almost 80 cm, that indicates the spinoff after interacting with the Gulf Stream. (The day 131 altimeter track is cut off at the northern edge of the GOAP region, so it does not completely cross the ring.)

Similarly, Fig. 6 shows ring E visible in an ascending
FIG. 5. Altimeter data superimposed on IR image from 2 May 1986. Ascending tracks through GOAP area from day 119 (29 April) and day 122 (2 May) cross a CCR (A) and the Gulf Stream. The altimeter data indicates that the CCR is larger than it appears in the IR image. The day 119 track also crosses a WCR (D).

FIG. 6. Image 4 days later with four GEOSAT tracks superimposed. The altimeter tracks cross the Gulf Stream, two CCRs, and two WCRs that are also visible in the IR image. The SSH data provides additional information on the sizes and strengths of the features.
Fig. 7. Image 10 days later with GEOSAT tracks superimposed. The IR imagery between 6 May and 16 May was completely cloud-covered. All the information during the intervening period came from altimetry.

Fig. 8. Infrared image showing CCR interacting with Gulf Stream. The day 73 GEOSAT track indicates a strong CCR with a 150-cm dynamic height depression.
track’s altimetric signal (year day 125). This WCR moved westward from its earlier position. Though this strong vortex is not visible in the IR image because of cloud cover, the altimeter shows almost 100 cm of relief. Figure 7 shows a repeated interaction between ring D and the Gulf Stream 10 days later. A descending altimeter track (year day 134) intersects this ring. It shows a strong, asymmetric signal that indicates the partly meander-like circulation with a large portion of the Gulf Stream signal south of the WCR.

e. Interpretation and difficulties

NORDA chose the northwest Atlantic region that contains the Gulf Stream and rings as a demonstration area because of the pronounced altimetric signal and the existence of a high-quality geoid. Figure 3 shows the GOAP area and the GEOSAT orbit’s ground-track laydown for a 7-day period during the primary mission (the first 18 months). Consecutive ascending or descending tracks were separated by 25.1 degrees of longitude at the equator as the satellite revolved around the earth about 14.3 times per day. The situation is essentially the same for the ERM orbit. Since the altimeter is a nadir-looking instrument with a field of view of only a few km, there are very wide gaps in coverage during a 1-day period, approximately 2100 km in the GOAP area. Even after a week there are large, diamond-shaped holes in the coverage.

The spatial scale of mesoscale features in the Gulf Stream area is about 100 km. The Gulf Stream’s daily position changes can be large (about 30 km), while the rings move slowly, 4 to 5 km per day on the average; occasionally they may shift 15 km per day. Obviously, altimeter coverage alone cannot describe the mesoscale field. NORDA chose satellite IR imagery to compensate for the altimeter’s lack of synopticity, and occasional in situ XBT measurements provided detailed information about the ocean’s vertical thermal structure at key locations.

The almost ever-present appearance of clouds is one of the detriments common to all present mesoscale interpretations in the Gulf Stream region when using IR. Experience indicates that although one IR image may reveal all or none of the Gulf Stream, typically about 30-40 percent is visible. This percentage differs with the season. During the summer months, seasonal surface heating obscures the IR signatures of older cold rings. In such conditions the altimetric signal becomes essential. Difficulties in the interpretation of altimetric signals in terms of mesoscale features stem from:

(i) the particular geometry of mesoscale features and altimetric tracks (important if no IR is available), and
(ii) geophysical corrections.

Oblique crossings of the Gulf Stream by the altimeter belong to the first category. A pass perpendicular to the Gulf Stream would have a strong, narrow SSH signal, but a pass at an acute angle would take longer to cross the Gulf Stream, and the signal would be spread out. Also, little or no Gulf Stream signal is apparent when the altimeter crosses an area of strong interaction between the Gulf Stream and rings (Fig. 6 shows an example). The ground track may also intersect a ring near its edge, making it appear small.

The main problems of the second category result from errors in the reference surface. The error connected with “smearing” of the Gulf Stream in the geoid was discussed in section 3b(3). A good example is the S-shaped altimeter signal in Fig. 6, in the ascending track for year day 125. It corresponds to case 2 of Fig. 2. This error appears to strengthen the warm ring’s signal in the north and falsely indicates a return current south of the Gulf Stream. Along GEOSAT-ERM ground tracks, estimates of the geoid profile which are relatively uncontaminated by the mean topography can be obtained as the difference between simultaneous dynamic topography profiles (from deep XBT sections) and GEOSAT-ERM overflights (Mitchell et al. 1989). Of course, such estimates are contaminated by the barotropic component of sea level (see Hallock et al. 1989).
Distortions and asymmetries of rings were observed due to errors in the reference surface. In general, CCRs are easier to detect than WCRs. The reasons are that warm rings very often interact with the Gulf Stream, the geoid is less well known in the area of the continental slope where WCRs exist, and WCRs have flatter profiles than CCRs of similar diameter. The balance of forces explains the last effect. In warm rings, the horizontal pressure gradient is aided by centrifugal force to balance the Coriolis force. In contrast, cold rings exhibit a large sea surface displacement because the Coriolis and centrifugal forces work in unison against the pressure gradient.

Our experience indicates that simultaneous IR and altimetry often agree in determining the northern Gulf Stream boundary, with precision limited by the altimeter data (14 km). But, there are cases when they disagree. The IR image in Fig. 8 indicates that the Gulf Stream meanders southward around the interacting cold ring. Altimeter data, namely the year day 70 ascending track, agree with IR images in this southern branch, but also show a continuation of the Gulf Stream as a bridge north of the ring. Figure 6 shows a sharp meander, perhaps in weak interaction with the CCR. The year day 125 ascending altimeter track shows the Gulf Stream's position shifted about 40 km north of where the IR image indicates. These cases are not unprecedented; Hansen and Maul (1970), Robinson et al. (1974), and Horton (1984) found that the 15°C isotherm at 200 m, considered to be the core of the Gulf Stream, can be considerably separated from the near-surface thermal structure. Perhaps in the above interactions the deeper portion of the Gulf Stream acts separately from the surface Gulf Stream and produces the surface topography seen in the SSH signal. It is also possible that part of the difference observed is due to a mismatch in time between the IR and altimetric observations.

It is sometimes difficult to establish whether meanders are pinched off from the Gulf Stream. Figure 10 shows a large cold-core meander extending 380 km southward. This meander is strong and never closes to create a cold ring. Fortunately, IR data are available to confirm this interpretation.

f. Preparation of mesoscale maps

NORDA used altimeter SSH residuals combined with Advanced Very High Resolution Radiometer (AVHRR) and XBT data to produce a depiction of the Gulf Stream's north and south walls and warm- and cold-core rings. This depiction consists of an alphanumeric description of the features' positions and strengths (i.e., sea-surface temperature gradients).

![Fig. 10. Infrared image for 9 November 1985 with superimposed altimetry. Note very large cold core meander extending 380 km southward.](image)
During the GOAP operational demonstration this description was sent as a Navy message and used as a "bogus" (a commonly-used Navy term for manually adjusted data, e.g., front and eddy locations) for FNOC's Expanded Ocean Thermal Structure three-dimensional thermal analysis (Clancy 1987). NORDA also provided the information in graphic form (the mesoscale map described in section 4a) as a quality-control measure. A 4- to 7-day sliding window of SSH and AVHRR data went into each of the twice-weekly GEOSAT mesoscale maps and alphanumeric descriptions.

Section 3 describes the treatment of the altimeter data during the operational demonstration. An average of two AVHRR images per day were received from each NOAA satellite. Those for which the area of interest was not totally cloud-covered were calibrated and "warped" to a Mercator projection at a resolution of 2.5 km. In some cases it was found helpful to combine channels 4 and 5 to create multichannel sea-surface temperature (MCSST) images, especially during the summer when high concentrations of water vapor often obscure the oceanic features in a single channel. The NORDA analyst displayed IR images in a format compatible with the altimeter to cover the area of interest with a 5-km resolution, but 2.5-km-resolution sections were available if needed. During the cloudy periods, composite images created from several days of IR data show more of the mesoscale features than individual images. Those "warmest-pixel" composites were created from a registered sequence of images by assigning to each pixel location the value corresponding to the highest temperature from all images in the sequence.

NORDA received daily BT data from FNOC. These data are collected by FNOC from various ship surveys without systematic distribution in relation to our purposes. The NORDA analyst used the profile's character and the depth of the 15°C isotherm to apply corrections to the mesoscale feature map.

Figures 5-8 and 10, which show SSH profiles superimposed on an IR image, illustrate the approach used in the GOAP mesoscale analysis, which is to combine complementary data types. Altimeter data displayed on an image of the Gulf Stream area helps the analyst to visualize the relationship between the two data types. The imagery's superior area coverage compensates for the altimeter's lack of synoptic (Leitao et al. 1979), while the mesoscale features' thermal signatures give information about their shapes. The figures also illustrate the altimeter's ability to penetrate cloud cover and reveal information not visible in the IR imagery. The analyst combines all of this information with the aid of interactive image processing, which allows color enhancement of IR imagery and provides the ability to overlay profiles of other data. The interactive aspect allows the analyst to view an image, manipulate it and observe the results, and continue to perform image processing operations until he is satisfied with the results. The addition of BT observations provided the interpreter even more information.

The analyst begins the GOAP interpretive procedure by displaying SSH profiles from passes within the area of interest, and uses a cursor to select positions of interest along each profile. The analyst also displays significant wave height, geoid height, tilt and bias correction, raw (altimeter-measured) range, water vapor correction, and tide height along the orbital pass ground track to check for data errors.

Figure 4 shows an example of an SSH profile used in an analysis. Selected points are assigned numbers and all data associated with each point are stored in a file. Figure 11 presents two other SSH profiles and the features derived from them.

Once a representative sample of SSH residuals are displayed and analyzed, the selected points are displayed against the common grid (Fig. 12). Four to seven days of data are generally displayed for each mesoscale feature map. This time represents a compromise between the amount of data necessary to complete the mesoscale map and the time scale of mesoscale motions characteristic of the Gulf Stream system. The most recent SSH profile receives the greatest weighting in the final mesoscale feature map.

The next step is the study of IR images from the same period. First, the analyst displays the most recent IR image on the common grid, and stretches the con-

![Fig. 11. Sea surface height residuals for GEOSAT orbits 7795 and 7802 on year days 251 and 252, respectively, showing identifiable mesoscale features.](image-url)
Fig. 12. Selected GEOSAT passes and various points selected along each nadir track to represent possible mesoscale feature locations for a 7-day period.

Contrast and brightness to enhance the features visible in the image. The analyst observes the imagery at a thermal resolution of 0.125°C in limited temperature ranges by selective enhancement of temperature "windows." Likewise, a "zoom" to a full-resolution display of a smaller area is possible if necessary to study detail.

Using a trackball to position the cursor, the analyst selects points along the Gulf Stream's north and south walls to represent their positions. Similarly, the analyst selects WCR and CCR centers and radii, and saves all the values to a file. The analyst repeats the process for older IR images in reverse chronological order. He then combines the SSH and IR data by displaying them together on the common grid. In many instances the north wall positions indicated by the SSH residual profiles and the IR imagery are within one SSH residual point, or 7 km, of each other. Using the most recent available data, the analyst constructs a continuous line depicting the Gulf Stream. In areas of no SSH residuals or IR imagery, the analyst uses his experience analyzing the Gulf Stream's behavior, and the Gulf Stream and ring positions from the most recent previous mesoscale feature map, to complete the new map.

Next, the analyst displays BT data on the common grid. Each BT's position and measured vertical temperature profile are displayed (Fig. 13). The depth of the 15°C isotherm is a key in the Gulf Stream area to evaluate the mesoscale feature map's correctness (Tracey and Watts 1986). If the 15°C water is below 460 m, then the BT is assumed to be in Sargasso water. If
no 15°C water is found or if it is above 100 m in summer, then slope water is assumed to be present. If 15°C water is present between 200 and 460 m and if the position is south of the Gulf Stream, then a CCR is indicated. A warmer profile north of the Gulf Stream suggests a WCR. This information is used to verify the existence of and locate features indicated by SSH residual data. Figure 14 shows a sample GEOSAT mesoscale map.

FNOC also makes the GOAP mesoscale product information available to NEOC, the regional oceanographic center whose area of responsibility includes the GOAP mesoscale test area. NEOC has found the information to be helpful, particularly as an indication of possible CCR activity in locations where surface thermal signatures are not visible in IR imagery. On several occasions, the GOAP product located a cold eddy that was subsequently verified by satellite imagery or BT data. Generally, NEOC finds that more eddies, both warm and cold, are evident in the GOAP product than are revealed by IR imagery alone.

5. Results

a. Winds, waves, ice

Shuhy et al. (1987) and Dobson et al. (1987) present information on the accuracy of GEOSAT wind and wave data. Tables 1 and 2, which contain information from Dobson et al. (1987), summarize some of the results.

Tables 1 and 2 show that the prelaunch accuracy targets for wind and wave measurements have been met or exceeded. It is more difficult to obtain quantitative assessments of the accuracy of the ice-edge data. However, comparisons with IR and visible satellite imagery are favorable.

<p>| TABLE 1. Wind speed accuracy (Buoys within 50 km and 0.75 deg pointing error). |
|-------------------------------|-------------------------------|</p>
<table>
<thead>
<tr>
<th>Goal</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rms</td>
<td>1.8 m s⁻¹</td>
</tr>
<tr>
<td>Mean</td>
<td>0 m s⁻¹</td>
</tr>
</tbody>
</table>

<p>| TABLE 2. Significant wave height accuracy (43 open-ocean buoys within 50 km of nadir tracks). |
|-------------------------------|-------------------------------|</p>
<table>
<thead>
<tr>
<th>Goal</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rms</td>
<td>0.5 m or 10%</td>
</tr>
<tr>
<td>Mean</td>
<td>0 m</td>
</tr>
</tbody>
</table>
Pickett et al. (1987) illustrate GEOSAT wave data. FNOC incorporates GEOSAT significant wave height data into a Visual Sea Height Analysis (Clancy 1987), which attempts to provide an accurate synoptic representation of global significant wave height. It uses the Fields by Information Blending (FIB) analysis technique (Holl et al. 1979) to map SWH observations less than 6 hours old into a Global Spectral Ocean Wave Model first-guess wave field (Clancy 1987). The FIB technique weights the wave height observations by time and grid point distance relative to the first-guess field and spreads their influence accordingly.

Hawkins and Lybanon (1989) provide details on the GEOSAT ice products and NPOC’s use of them. The altimeter’s all-weather capability has been an important addition to the NPOC databases, since cloud cover can drastically curtail visible and IR viewing, and passive microwave data has coarser resolution. Hawkins and Lybanon (1989) present several illustrations that show GEOSAT along-track ice index values superimposed on satellite images. They clearly indicate the ice index’s ability to delineate the ice edge, and suggest that the index may be sensitive to ice concentration or ice type. Ongoing NORDA research efforts are aimed at investigating this possibility, and at extracting additional sea-ice information from the altimeter waveform data (e.g., Chase and Holyer 1988).

b. Mesoscale results

The GOAP mesoscale analyses comprise a large dataset, from which statistics on Gulf Stream and ring positions and velocities can be obtained. Comparisons with other datasets tend to confirm the accuracy of the GOAP results. The relative contributions of altimetry, IR, and analyst estimates to the GOAP mesoscale analyses vary, but average about one-third each. Altimetry contributes as much information as IR imagery, so it is clearly an important addition to the analyst’s list of information sources. Some of the problems encountered in using altimeter data are summarized later in this section.

The mean, standard deviation, and extreme positions of the Gulf Stream during the period March 1986 through November 1987, as derived from the GOAP mesoscale analyses, are presented in Fig. 15. The data are consistent with data recently published by Auer (1987). The two-tiered Gulf Stream shows east–west trends along 38°N from 71° to 65°W and along 40°N from 62° to 50°W. The Gulf Stream’s northward movement occurs in the wake of the New England Seamount Chain.

The mesoscale products have been compared qualitatively with similar products from NEOC. Portions of the Gulf Stream pass over inverted echo sounder (IES) installations maintained by the Regional Energetics Experiment (REX) (Mitchell et al. 1987). There were two IES arrays, deployed across the historical mean Gulf Stream path near 67° and 58°W. Teague and Hallock (1989) used the IES measurements to estimate the Gulf Stream’s position. Their analysis was based on a procedure used by Watts and Johns (1982). Preliminary results of a comparison of IES and GOAP analyses are presented in Table 3. “Good agreement” means within 20 km; “favorable agreement” means 20–50 km displacement. This table shows at least favorable agreement between the IES and GOAP analyses in 79 percent of the overall data, with 75 percent agreement east of the New England Seamounts and 83 percent agreement west of the seamounts.

Table 4 contains information that shows the relative importance of altimetry, IR, and estimates for determining the position of the Gulf Stream’s north wall. The monthly percentages were derived from the Navy messages prepared at NORDA (the alphanumeric mesoscale products), which include latitudes and longi-

![Fig. 15. Gulf Stream mean position with standard deviation and extremes. The results shown are derived from the GOAP mesoscale analyses.](image-url)
The altimeter consistently contributed to the preparation of the mesoscale product; the relative size of the contribution depended on the quantity of cloud-free IR imagery available and the amount of altimetry data recovered. Due to changes in GEOSAT that occur as the spacecraft travels from darkness into sunlight, the altimeter occasionally does not acquire lock on its return signal until after it passes the GOAP demonstration area. (This problem primarily affected descending tracks in the Northern Hemisphere.) The altimeter’s contribution to the mesoscale product was relatively constant at about one-third of the information, but varied from a low of 24 percent in June and July 1987 to a high of 38 percent in May 1986. The contribution from IR imagery had a higher variability, from 23 percent in February 1987 to 54 percent and 55 percent in July 1987 and June 1986, respectively.

Although atmospheric frontal passages tend to leave clear, dry areas as they pass, during the winters of 1986 and 1987 the fronts appeared to stall before leaving the GOAP area, causing portions of the Gulf Stream to be cloud-covered for long periods and decreasing the contribution of the IR imagery to the mesoscale product. During the summer, clouds and high atmospheric water-vapor content hamper the computation of accurate sea-surface temperature values. Nevertheless, atmospheric conditions change fast enough to give the analyst more information from the IR imagery during summer than winter. Although exact temperatures and minor thermal changes are not visible, the Gulf Stream’s north wall can be located. The amount of information provided by IR imagery to a mesoscale product averaged approximately one-third of the total.

The “estimated” portion of the mesoscale product also depended on the amount of IR imagery. During periods when more IR images were available the estimated portion decreased, and vice versa. A single altimeter point located on the Gulf Stream north wall helped the analyst to estimate how the Gulf Stream moved in a cloudy area.

The GEOSAT orbit’s ground-track laydown does not provide synoptic coverage, as discussed in section 4e and illustrated by Fig. 3. It is entirely possible for the altimeter to miss mesoscale rings for days or even weeks, and even if the altimeter observes a feature the ground-track pattern may not intersect that feature again for an extended period. So, there may be only one cross section, through any part of the feature, as evidence for the feature when the analysis is performed.

As Figs. 11 through 13 illustrate, the mesoscale features do not always appear as obvious choices to the analyst. Section 4e pointed out that much variability in signal similarity arises from the angle at which the GEOSAT pass crosses the Gulf Stream. Water vapor may also affect the selection of mesoscale features. The appearance of an individual CCR or WCR also varies depending on the portion of the ring that the pass crosses. Crossing a ring edge results in a smaller signal (in both extent and amplitude) than crossing a ring center. Because a ring’s size and strength change with age, the SSH signal also varies with a ring’s age. It is important to note that young rings include moving water around their perimeters, reflected in the SSH as part of the ring, which does not have the same properties as water in the ring’s true interior. Geoid errors also distort the altimetric signal, as the frequent presence of clouds diminishes the utility of IR images.

During the first 18 months of GEOSAT the ground tracks defined a tightly spaced global mesh, but the nonrepeating ground track pattern did not allow the clear separation of the geoid from the instantaneous topographic components of sea level, except in areas where a gravimetric geoid was known. One reason for
the choice of the GOAP mesoscale test area was the existence of a high-quality geoid for the northwest Atlantic Ocean. The satellite’s ground track repeats almost exactly every 17 days during the ERM, so an analyst can use an along-track ensemble mean “surface” where no precise geoid is available.

6. Conclusions

The GEOSAT altimeter’s all-weather capabilities and its received pulse’s relationship to several geophysical parameters make it a desirable sensor for oceanographic and meteorological investigations. Surface wind speed and significant wave height are produced with minimal processing from the shape and power of the return microwave pulse. An ice index related to the presence or absence of ice, and therefore the sea ice edge, can also be generated from the reflected microwave pulse. Significant ocean currents produce a variable sea surface topography that is easily measured by the GEOSAT altimeter.

The GEOSAT altimeter’s microwave pulse is affected by atmospheric water, but the degradation is not so great that Gulf Stream mesoscale features are not identifiable. Although atmospheric water vapor signals are indistinguishable from the oceanographic signal, they are smaller than the signals that oceanographic features produce in the GOAP area. In other areas this would not be the case, and a water vapor correction would probably be needed (Phoebus and Hawkins 1990). If clouds are present, the SSH residuals may yield the only certain mesoscale feature positions in the mesoscale map.

An added capability of the SSH residual is the ability to detect the surface topographic manifestation of mesoscale features having no surface IR expression. Cheney (1982) points out that dynamic height is largely a function of thermocline depth, and found that there is a high correlation between dynamic height and the depths of the 15°C isotherm, the 17.5°C isotherm, and the temperature at 350 m. The possibility of inferring subsurface thermal structure from sea surface topography was also noted by Khedouri et al. (1983).

During the GOAP operational demonstration, significant wave height and surface wind speed were processed and transmitted automatically to FNOC to be used as input data and quality control information. Ice index values were plotted and the graphics transmitted to the Joint Ice Center in Suitland, Maryland, to aid in the identification of the sea ice edge. Sea surface height residuals were processed daily and analyzed twice each week to generate a Gulf Stream region mesoscale map.

The validity of the mesoscale map is based on the interpretation of SSH residual patterns as oceanographic features. The effectiveness of the interpretation is presented in numerous comparisons of SSH residuals and satellite IR imagery. In fact, the SSH residuals and IR imagery are used in concert with in situ temperature profiles to generate the most accurate mesoscale map possible. Statistics from a time series of these mesoscale maps indicate that satellite IR imagery and GEOSAT SSH residuals each contribute approximately one-third of the information for any mesoscale map. The remaining one-third is analyzed subjectively.

Oceanographic information derived from GEOSAT altimetry has already proven to be of value in depicting mesoscale circulation and significantly increasing the quantity of ice edge information available. The altimeter’s ability to provide oceanographic information when other sensors suffer from impaired viewing further increases its value. NORDA is beginning to extend the techniques developed for GOAP to other portions of the world ocean, and is developing assimilation techniques to use altimeter data more directly in numerical models. Many other researchers are reporting a variety of work with GEOSAT data. The research studies and applications based on GEOSAT data clearly demonstrate the altimeter’s usefulness as a tool to collect timely, accurate oceanographic information.

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